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EBT Theory Workshop Panel Report

February 1979

U.S. Department of Energy
Assistant Secretary for Energy
Office of Fusion Energy
Division of Applied Plasma Physics

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EBT THEORY WORKSHOP

A PANEL REPORT TO THE DIRECTOR FOR APPLIED PLASMA PHYSICS, OFFICE OF FUSION ENERGY

Panel Members

Abraham Kadish, Panel Chairman, Department of Energy
Richard Aamodt, Science Applications, Incorporated
James Callen, Oak Ridge National Laboratory
Harold Grad, New York University
Gareth Guest, General Atomic Company
Nicholas Krall, JAYCOR
Niels Winsor, Naval Research Laboratory

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EBT THEORY WORKSHOP PANEL REPORT

I. Introduction

An EBT Theory Workshop was held on Wednesday, January 17, 1979, at DOE Headquarters in Germantown, Maryland. The Workshop Panel was composed of R. Aamodt (SAI), J. Callen (ORNL), H. Grad (NYU), G. Guest (GA), A. Kadish, Chairman (DOE), N. Krall (MAYCOR), and N. Winsor (NRL). C. L. Hedrick of ORNL was present as a consultant to the Panel. This EBT Workshop was the first of several planned by APP to optimize the usefulness of the EBT proof-of-principle experiment, EBT/POP, scheduled to begin operation in 1982-1983.

The purpose of the Workshop (see Appendix A) was to identify the most important physics issues that need to be addressed in order to assure the optimal design and timely interpretation of the EBT/POP. The Panel was also asked to assess the levels of effort required to obtain priority information on time scales compatible with the projected dates for operation of EBT/POP.

The fiscal year cost anticipated for the effort recommended by the Workshop Panel (excluding costs for computing) is estimated to be approximately $3.5M. EBT theory is currently funded at a level of approximately $700K per year.

II. Summary of the Workshop Panel's Recommendations

For emphasis, the priority problem areas identified by the Panel are grouped into six categories. These categories overlap as a result of the impact that information from any one category would have on the others. The categories chosen were Magnetic Geometry and Particle Orbits, Macroscopic and Microscopic Equilibrium and Stability, Ring Physics, Transport, Heating, and Edge and Divertor Effects. The table below identifies the high priority areas within these groupings, together with a summary recommendation of levels of effort.

CATEGORY	MANPOWER/YEAR	NEAR TERM PRIORITY AREAS
A. Magnetic Geometry & Particle Orbits	3	Guiding Center Orbits and Coil Design Effects
	3-4	Code Development, Validation, and Documentation
B. Equilibrium & Stability	1-2	Equilibrium Solvers
	3-4	Macroscopic Stability
	2	Coupling Effects
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C. Ring Physics	5	Equilibrium, Stability, Heating Coupling Effects, Radiation Effects
D. Transport		
Neoclassical Transport	8	Kinetic Analysis of Transport Coefficients including Fokker Planck Calculations
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E. Heating		
ECRH	5-6	Microwave Coupling, Propagation, and Absorption
Neutral Beam and Other RF	4-6	Wave Coupling, Propagation, and Absorption
F. Edge and Divertor Effects	5	Power Balance and Heat Flow

The Panel feels these are the basic areas that need to be addressed and receive sustained attention if important problems are to be anticipated prior to machine operation in 1982-1983, and if a necessary theoretical base is to be available for the timely interpretation of data from the experiment.

The Panel recognizes that the priority problem areas identified do not include all of the potentially important areas of EBT theoretical physics. The Panel assumed that EBT/POP would have circular cross section and that ECRH would be the major source of heating. If these assumptions turn out to be incorrect, the list of priority items for theoretical research will require some obvious modifications. However, the techniques developed in the areas identified here will permit useful analysis of most conceptual approaches.

In addressing the need for theoretical research in support of EBT/POP, the Panel omitted from its priority category those areas which, while important and interesting, could not be addressed with the expectation of obtaining significant results on time scales relevant to the operation of the experiment. The research areas recommended here will, however, provide a strong theoretical foundation for research in these other areas in the event that the EBT program broadens at a later date.

III. The Panel's Recommendations

A. Magnetic Geometry and Particle Orbits

Energy containment, transport, and equilibrium for a given magnetic field configuration all depend essentially on individual particle orbits.

Knowledge of orbits in fields generated by different coil, hot plasma, and divertor configurations is required for optimal machine design and for general physics understanding of EBT/POP. Particle orbits in EBT are affected by the plasma diamagnetic currents, ambipolar electric fields, and toroidal effects. For example, a particle which is mirror confined to a single cell on the inside of the torus may, after drifting in the poloidal direction, become a passing particle as it moves to the outside of the torus.

The Panel recommends that an intensified research effort should be undertaken to investigate particle orbits in EBT configurations for the purpose of determining optimal confinement and as input for transport coefficients.

Present-day codes can, in principle, determine drift orbits in specified, ad hoc, magnetic and electric fields. In practice, vacuum magnetic fields form the basis for most attempts to optimize the magnetic geometry and estimate the basic transport rates. None of the finite Larmor radius codes which are now available include self-consistent electric and magnetic fields. That is, they do not account for field variations resulting from particle motion. The timely development of such comprehensive codes will probably require the superposition of component codes which would allow a search by iteration for self-consistent configurations. For example, high-beta anisotropic equilibrium solvers would be useful in this regard to compute the transport rates and the α-particle modification of the magnetic field. These transport rates could be used in a transport model to deduce self-consistent pressure and current profiles.

Some codes do already exist which might in principle be useful as components in such a program. However, these codes are not readily available to the plasma theory community, and many of these codes are in need of significant modification. Few of these have reached the stage of completion and documentation needed for the present program.

The Panel recommends that a code documentation program should be initiated as an addition to the EBT theory program and given continuing support in order to make fundamental codes available rapidly throughout the broadened community of EBT researchers.

Both the particle orbit effort, which is estimated to require a team of approximately three scientists, and a code development, validation, and documentation effort of similar manpower commitment, should be continuing efforts. Although EBT/POP would be primarily designed using modifications of existing codes, both of these efforts should be viewed as continuing sources of physics input for modeling EBT physics, and interpreting data from EBT experiments.

B. Equilibrium and Stability

Although EBT does possess mirror symmetry along the magnetic axis, it is not toroidally symmetric. As a result, EBT equilibria cannot be analyzed as a two-dimensional problem. While this precludes the use of existing tokamak equilibrium codes, three-dimensional techniques have been developed and can be brought into widespread use via the MFECC Network, provided manpower is devoted to documentation and improvement of existing

codes. In addition, equilibrium solvers for straight bumpy cylinders are also useful. Although toroidal effects are absent in these solvers, these simpler codes are sufficiently economical to permit broad exploration of high-beta effects, particularly in the large aspect ratio range relevant to the EBT/POP experiment. Macroscopic stability theory will require investigations of both ideal and non-ideal MHD and guiding center fluid models. Some codes are already in place which can be used for this purpose either as they now are constituted, or they can be upgraded to include additional effects in the near future. Some studies will require new codes.

The Panel believes that a team of three to four scientists could obtain significant results in macroscopic stability in about two years. This would be well before EBT/POP begins operation if the effort in this area is initiated by early FY 1980. The effort in microstability recommended by the Panel would be comparable in size. Judicious modeling will allow a continuously improving understanding of microstability with a capability for impact on the interpretation of data not only from EBT-I and EBT-S, but from EBT/POP. This research may be vital to understanding the transport scaling of EBT should the neoclassical model fail to account for observations in EBT/POP.

The Panel believes that a study of the coupling effects between various components of the EBT plasma could yield significant information on operating regimes for required machine and plasma parameters in two to three

years if a team of two scientists were dedicated to this task. Their work could be calibrated against data from the existing EBT-S and original EBT-I experiments in which the unstable C&M and stable T modes of operation have been identified. The results of this work, if it is started by FY 1980, would provide guidance for steady-state, stable operation of the POP device by the time it is scheduled to begin plasma experiments.

As indicated in the previous discussion of particle orbits, the Panel recommends that an effort be initiated to upgrade and extend equilibrium codes for the EBT configuration. The Panel's expectation is that a one year, one to two man effort should suffice for the most pressing applications anticipated for these codes. The resulting codes would have immediate impact on assessing the desirability of various magnetic field configurations and on the recommended transport calculations which are described below.

C. Ring Physics

The annular rings in the EBT mirror cells stabilize a configuration which would otherwise fail to satisfy well-known stability criteria. While the rings have been produced routinely for the EBT-I and EBT-S experiments, and have been observed to be stable in the presence of a cold, low-beta toroidal plasma, their behavior when coupled to a hot, high-beta plasma has not been adequately investigated.

The Panel recommends that an aggressive research effort be initiated to investigate ring physics. It believes the physics of the rings is

sufficiently important, and spans a sufficiently broad area in need of research, to require two teams of dedicated scientists (five to six men/year). With such an effort, the Panel believes that in three to four years a reasonable understanding could be obtained of ring equilibrium, heating, stability, radiation effects, and transport and ring coupling effects with other EBT plasma components.

These studies should supply valuable information for interpreting data on power requirements for heating, plasma beta limitations due to breakdown of stability provided by the hot annulus, and disruption of the annulus by the bulk plasma, as well as providing input for those areas of transport modeling which couple the various components of the EBT plasma.

D. Transport

Given the existence of macroscopically stable equilibrium for steady-state EBT operation, transport processes will ultimately determine the economic feasibility of the concept as a reactor. In the more immediate future, an understanding of the possible transport mechanisms in EBT will be essential to interpreting data from EBT-S and EBT/POP.

One of the more controversial EBT issues in the recent past has centered around the transport scaling of EBT. Available theories predict that if the dominant transport loss in EBT is neoclassical, then EBT possesses very favorable scaling properties. The desirability of EBT as a reactor

concept resides, in large measure, on the hope that such a favorable scaling will in fact prevail. On the other hand, the possibility exists that there may be microinstabilities in EBT which cause anomalous transport to be an important contributing transport mechanism in EBT at higher temperatures than those achieved thus far. If this should be the case, the advantages of an EBT reactor over other reactor concepts may be marginal. Existing experiments and the available EBT data base are consistent with neoclassical losses but are inadequate to permit confident extrapolation to hotter and more dense versions of EBT. EBT/POP will probably provide a much more complete determination of transport scaling in EBT.

In order to assist in the accurate identification of the dominant transport mechanism and to exploit the implications of the observed scaling, such as reactor dimensions and profile control requirements, the Panel recommends that an increased effort in transport theory be initiated and maintained for the EBT concept. The Panel recommends that until evidence to the contrary is available, the major thrust of this effort should emphasize research on neoclassical transport. The Panel recommends that at least two teams (about eight scientists) be dedicated to this effort to ensure both a broad based and a competitive program. At the same time, a smaller effort should explore possible anomalous transport losses (about two scientists). These programs should involve the calculation of transport coefficients for both ions and electrons. The

neoclassical effort should include the effects of non-Maxwellian distributions, and if feasible, eventually include Fokker-Planck calculations. Since both these efforts will ultimately require input from particle orbit and equilibrium studies, self-consistent results for EBT/POP may not be available in less than three years.

The Panel recommends that an ongoing transport simulation and fueling theory effort be supported. The consensus of the Panel is that initial efforts in this area should at the outset be dedicated primarily to highest possible quality 1-D and 1 1/2-D modeling. Kinetic modeling should, as soon as is practical, include important two-dimensional effects, such as those due to the finite toroidal extent of the annuli. The Panel further recommends that calculations in two and three dimensions be undertaken utilizing classical macroscopic transport models. The former effort should involve a team of two to three scientists and be viewed as a continuing effort. The latter should involve approximately two scientists and yield significant results capable of assisting in the interpretation of data from the POP experiment in about three to four years.

E. Heating

Past EBT experiments have operated at toroidal plasma ion and electron temperatures limited to approximately one hundred eV and several hundred eV, respectively. These experiments utilized ECRH to both drive the annular rings and heat the toroidal plasma. ECRH power generation

technology and overall power requirements limited both the operating density of these experiments and the power available for cw heating. It is expected that EBT/POP will be limited to similar considerations, despite the availability of cw tubes of higher power and frequency.

In order to optimize the performance of the POP experiment, the Panel recommends that an intensive theoretical effort be undertaken to investigate microwave propagation and absorption in EBT. In order to optimize microwave heating capabilities within the anticipated limitations of microwave technology, the Panel further recommends that theoretical efforts in multifrequency heating also be undertaken.

The Panel believes that an understanding of ECRH (coupling of input power to other plasma modes) is fundamental to understanding EBT physics. Consequently, the Panel recommends that a major effort be made in this area. The effort should involve at least two teams (totaling five to six scientists) and that this effort should be a continuing one.

In anticipation of the possibility that additional heating mechanisms may be necessary if EBT/POP is to achieve the temperatures required for successful demonstration of the EBT concept, it is recommended that theoretical studies be undertaken for EBT in neutral beam heating and other types of rf heating besides ECRH, such as ICRH, lower hybrid, and Alfven wave heating. These efforts should also be continuing and should involve a total of at least four scientists to begin with, and increase in level of effort with time.

F. Edge and Divertor Effects

The energy and particle containment properties of the POP experiment will not only be influenced by stability and transport properties of the EBT configuration but by the effects of the physical boundaries, such as walls and divertors. These boundaries, together with the magnetic geometry and its effect on particle orbits, will strongly influence heat loss and the distribution and removal of impurities from EBT/POP.

The Panel recommends that a large ongoing theoretical effort, starting with about five scientists and increasing in time, be undertaken to study edge and divertor effects. Emphasis in these studies should be placed on particle and energy refluxes and their impact on material walls for various designs.

The Panel believes that these studies, if initiated in the near future, can impact both on the design of, and interpretation of data from, the POP experiment.

ACKNOWLEDGEMENT

The Panel wishes to thank Jim Decker, Director of Applied Plasma Physics, for an informative discussion of the status and objectives of the DOE alternate concept program. The Panel also wishes to acknowledge the valuable assistance of C. L. Hedrick, both in the Panel's discussions and for the materials he prepared for the Panel prior to those discussions. Finally, the Panel wishes to thank Bill Dove of APP for alerting the Workshop participants to some of the concerns of the Advanced Fusion Concepts Branch.

SIGNATURES OF THE EBT THEORY WORKSHOP PANEL:

Richard Aamodt
Science Applications, Inc.

Gareth Guest
General Atomic Company

James Callen
Oak Ridge National Laboratory

Nicholas Krall
JAYCOR

Harold Grad
New York University

Niels Winsor
Naval Research Laboratory

Abraham Kadish, Chairman
Office of Fusion Energy

APPENDIX A

JAN 5 1979

Prof. Harold Grad
Courant Institute of Mathematical Sciences
New York University
251 Mercer Street
New York, NY 10012

Dear Harold:

An EBT Theory Workshop will be held on Wednesday, January 17, 1979, at the U.S. Department of Energy Headquarters in Germantown, Maryland. This letter is an invitation for you to participate as a panel member of the Workshop. The panel members will be R. Aamodt (SAI), J. Callen (ORNL), H. Grad (NYU), G. Guest (GA), A. Kadish, Chairman (DOE), N. Krall (JAYCOR), and N. Winsor (NRL).

The purpose of the Workshop is to identify the most important physics issues in need of address in order to assure the optimal design of, and timely interpretation of data from, the EBT proof-of-principle experiment which is scheduled to begin operation in 1982-1983. In addition to identifying important EBT physics issues, the panel members are also requested to assess the levels of effort required to obtain priority information on a timescale compatible with the projected dates for operation of the POP experiment.

The conclusions arrived at by this panel will provide guidelines for the U.S. EBT theory effort over the next few years. The panel will have a unique responsibility and opportunity to impact on the direction and success of a major component of the magnetic fusion energy program. You have been invited because your expertise and your position in the fusion theory community will make your contributions to the Workshop particularly valuable. I hope that you will be able to participate. If you are unable to participate, please notify me as soon as possible.

In anticipation of a favorable reply, I have arranged accommodations for you for the evenings of January 16 and 17, 1979, at the Washingtonian Motel in Gaithersburg. If you wish to have your reservations guaranteed in the event of a possible late arrival, you must arrange for this on your own. The Washingtonian's phone number is (301) 948-2200. I will be sending you, under separate cover, additional information concerning scheduling as well as documents which you may find informative in preparing for our deliberations.

I look forward to a fruitful meeting and to seeing you soon.

ET-86

Sincerely,

AK

1-5-79

Abraham Kadish

ET-86

Fusion Theory & Computer
Services Branch

REP

Division of Applied Plasma Physics
Office of Fusion Energy

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cc:
J. Decker, ETM
R. Price, ETM
W. Ellis, ETM

ET-86:AKadish:jlk:33287:1-5-79

Identical letters sent to:

J. D. Callen (ORNL), Richard Aamodt (SAI), N. A. Krall (JAYCOR),
Gareth Guest (GA), Niels Winsor (NRL)

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